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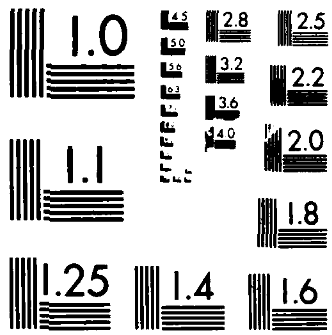
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Progress was made in a number of topics, including algebraic, adaptive, surface and interactive grid generation. Seventeen papers and one Ph.D. resulted, including such titles as "Alternating direction adaptive grid generation," "The local redistribution of points along curves for numerical grid generation", "Automatic algebraic coordinate generati and "The geometric construction of pointwise distributions or curves." In the first paper, an improvement was made for the alternating direction adaptive grid generation method. In the second paper, a basic tool for interactive grid generation was developed from an earlier theory of weights. In the third paper, the basic formulations of algebraic transformations were extended by forming Boolean sums of multisurface transformations and, by appropriate caupositiars, lifting the results to curved 2-D surfaces. In the fianl referenced paper, the capability to accurately partition the available grid points among various properties was established along with the simultaneous specification of grid spacing from the boundaries.

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Investigation of Three-Dimensional Mesh Generation

with Precise Controls

FINAL REPORT

Principal Investigator: Peter R. Eiseman

(May 1, 1982 to September 30, 1986)

Columbia University
New York, New York 10027

Grant Number: AFOSR-82-0176

The Last Grant Year

In the fourth grant period from October 1, 1985 to September 30, 1986, progress was made in a number of topics and was reported upon in a number of instances. The topics consisted of algebraic, adaptive, surface, and interactive grid generation. The reporting consisted of two written papers and six oral presentations.

In the first paper, an improvement was made for the alternating direction adaptive grid generation method [1]. This was presented at a conference in Beijing, China and appeared in the subsequent proceedings [2]. Recognizing the need for grid smoothness, each directional sweep in the process was replaced by a predictor-corrector format. Here, the predictor phase is occuppied by the active element of curve by curve equidistribution for given weights while the corrector phase is a global low pass filter that is inserted for derivative smoothness. By this reformulation of each directional sweep, the level of severity in the applications can be substantially increased without a sacrifice in efficiency. The result is a robust algorithm that retains the computational speed of its predecessor. To demonstrate the speed and robustness, an initial three-dimensional Cartesian grid was adaptively moved onto a variety of complicated disturbances, one of which was displayed in the paper [2]. There, the adaptation occurred within about 7 or 8 minutes on the IRIS 2500 (MC 68010) and provided the desired resolution about two intersecting ellipsoids that each also intersected the region boundaries.

In the second paper, a basic tool for interactive grid generation was developed from an earlier theory of weights [3]. It was presented

at a conference in Landshut, West Germany and appears in the associated proceedings [4]. From the theory of weights, a twist function arose for the purpose of inserting local pointwise clusters within given grids on arbitrary curves. The generic form of such clusters is described as a smooth expansion of the grid spacing from the perimeters of the specified cluster region that is then followed by a compression onto the cluster center as that center is approached. The expansion is required since smoothness is demanded at the perimeters and since the number of grid points is not altered. In the application, the twist function became a function subroutine. In higher dimensions, a bump function was established for transverse direcitons so that a twist could be kept at full strength for an interval and then smoothly phased out. This resulted in a bump function subroutine that provided a multiplicative factor for the twist. With the whole process being formulated in the logical index space with local multilinear interpolation being employed to transport the results to physical space, the developed algorithm became quite general. To describe this generality, we note that local clusters can be created in given grids regardless of how such grids were generated. The objects about which clustering is specified are points, coordinate curve segments, sections of coordinate sheets, or combinations of these. By a slight generalization of the twist function, volumetric enrichment was also demonstrated.

While the application of the basic clustering operation can be accomplished in a fixed programmed manner, it is ideally suited for the more dynamic interactive environment. This occurs because of the

simple algebraic formulation. That leads to a rapid computational response to user input which simply consists of a specified fractional decrease for the spacing at the object together with index locations to describe the region and the object.

In the general area of algebraic grid generation, another derivative continuous local interpolant was developed. Unlike the previous piecewise quadradic construction reported in [5], the use of a single trigonometric construction was established for a local interval under the assumption that the interpolation points are uniformly distributed. This provides a simpler formulation at the expense of a more costly computation that might not be too much of a limitation with the currently available workstations.

In the earlier case of the more efficient piecewise quadradic construction [5], another interesting development has occurred. Namely, it has provided the impetus for some of the major spline theorists to rethink their past developments. The reason is that the constructed piecewise quadradics were local and cannonical at the same time. The new idea to them was the insertion of intermediate points that were used for construction, but not for interpolation. The utility is that the interpolation is a linear combination of such locally constructed functions where the linear coefficients are the actual values of the function being interpolated. For approximation theoretic purposes, high polynomial accuracy is achievable while for grid generation, a bias towards curvature control is employed instead. Unlike the general use of splines, the interpolation can be done explicitly rather than implicitly. A further extension in the

approximation theoretic direction was recently undertaken by C.A. Micchelli (of IBM T.J. Watson Research Center at Yorktown Heights, NY) and will be formally reported by Micchelli et al. in Numeriche Mathematik.

On the topic of surface grid generation, work has progressed with the doctoral thesis work of my student Yi Wang. In this work, we are developing an algorithm where surface grids can be generated in a multiblock topological format with automatic and active curvature clustering as well as the further potential to cluster for other somewhat arbitrary purposes. The surface grid development represents an extension and refinement of the earlier mean value relaxation procedure [6] that was devised for adaptive purposes.

In the adaptive area, my other student, Michael Bockelie is progressing on extensions and refinements of the alternating direction method. The main focus is in two dimensions where the fundamental aspects of curvature attraction and orthogonality forces were considered and where the coupling with a PDE-solver is to be developed. As a demonstration of the method, the first test cases that have been selected will be a study of shock-vortex interaction. The results should also be of interest in the areas of acoustics and turbulence. Moreover, with certain boundary and initial conditions, there are previous finite difference and spectral simulations that can be used as a basis for comparison.

Finally, towards the end of the grant period, there was a sequence of invited review talks. The first was for the First World Congress on Computational Mechanics and was held at the University of Texas at

Austin in September 1986. There, I was invited to present a lecture, to organize a session by inviting other lecturers and to chair that session. As other speakers, I invited Joe Thompson, Joe Steger (with John Benek), and Bob Smith (with Lars-Erik Eriksson). The topics were block-structured grids, overlapping grids, algebraic grid generation, and adaptive grid generation. I chose the subject of adaptive grid generation for myself and presented an overview and synthesis of virtually all methods that employ movement as a primary mechanism. I also encouraged all of my speakers to submit written versions for a postconference journal publication. Everyone complied with this request, and as a result, there will be a grid generation section in the journal. In my case, the actual writing occurred in the next grant.

After the Texas conference, I was a primary invited speaker at the Dutch Numerical Mathematics Conference at Woudchoten near Zeist in the Netherlands from September 29 to October 1, 1986. There I delivered two one-hour talks. The first was a general review of grid generation while the other was a review of adaptive grid generation. In the next grant, which officially started on October 1, my trip continued by giving more specialized lectures at the National Aerospace Laboratory-NLR (Amsterdam, the Netherlands) and at Dornier (Friedrichshafen, West Germany).

Upon returning from the trip, a general review of numerical grid generation that followed the essence of the Dutch Numerical Mathematics presentation was prepared in response to an invitation from A.K. Noor for a chapter in the upcoming ASME volume entitled

"State-of-the-Art Surveys in Computational Mechanics." The writing, of course, occurred in a subsequent grant.

The Earlier Grant Years

In the earlier periods of this grant, the details were reported in the various interim reports. The subjects included virtually all aspects of grid generation. In addition, a doctoral thesis was completed by my first student, Gordon Erlebacher, who subsequently joined the Computational Methods Branch headed by Douglas L. Dwoyer at NASA Langley Research Center. There, Dr. Erlebacher has progressed with great success.

To summarize the overall activities here, a list of additional references is provided [7]-[14] and is to be considered along with [1],[3], and [6]. This included conference presentations at the APS Conference [11] in 1982, at Nashville [7]-[8] in 1982, at Houston [6] in 1983 (in the volume ASME FED-Vol. 5), at Danvers, MA [1] in 1983 (in the 6th AIAA CFD Conf.), at Snowmass, CO [10] in 1984 (in the AIAA Fluids, Plasma Dyn., and Lasers Conf.), and at Hilton Head Island, SC [13]-[16] in 1985.

In addition, the transfinite form for the multisurface transformation that was discussed in [8] in conjunction with orthogonality also provided the basis from which the subsequent development of a control point form of algebraic grid generation emerged in the next grant. That form preserved an interior tensor product format while permitting a selectively applied transfinite operation for the various boundaries. The transfinite conformity with

prescribed boundaries appears there only locally. The results will be reported in Montreal in 1987 for [17] under AFOSR-86-0307.

Under the first period of the grant support, (from May 1, 1982 to September 30, 1983), mathematical developments were performed on algebraic, adaptive, surface, and orthogonal transformations. Algebraic transformations were extended by forming Boolean sums of multisurface transformations and, by appropriate compositions, lifting the results to curved 2-D surfaces. The basic formulation was reported upon in [7] and [8]. In [7], it was viewed from the perspective of an eventual insertion into the automatic algebraic grid generation code that was developed for NASA. In [8], the mathematical formulation was given for arbitrary 2-D surfaces on which an orthogonal grid was to be constructed by means of orthogonal trajectories.

Surface grid generation was undertaken simultaneously with the development of adaptive grid strategies. Each adaptive strategy was based upon the formation of an abstractly defined surface which contains all of the pertinent solution properties that are in need of resolution for an accurate numerical simulation of the phenomena under study. With the pertinent properties expressed in the form of a single abstract surface over physical space, the primary adaptive objective is to put or push the points into positions which most accurately represent the surface. This same objective also appears when arbitrary 2-D surfaces are used as boundaries for 3-D regions. Although the abstract surfaces for adaptive purposes are defined over physical space, the various adaptive strategies that were developed

are applicable to the arbitrary surfaces required to bound 3-D regions. The strategies are mean value relaxation [6], alternating direction [1], and triangular [9]-[11]. The development for mean value relaxation [6] was done entirely under this grant. The theoretical basis for the alternating direction approach [1] was established under this grant and continued under NASA sponsorship (NAG1-355) culminating in a code at NASA Langley. The adaptive triangular methodology was developed with my doctoral student, Gordon Erlebacher, for his thesis research. The primary portion of this work was supported by the AFOSR grant with the remainder by grants from NASA and DOE.

In all of the techniques, curvature is the primary mechanism which is used to get a better resolution of a surface. The main building block is normal curvature. In the triangular mesh case, mean curvature is used because of the mesh structure. The better resolution comprises both an increased number of points in regions where the surface changes direction and an alignment with those regions. In addition, geodesic curvature is considered for nontrivial surface boundaries.

During the second period of the grant from October 1, 1983 to September 30, 1984, the development of algebraic and adaptive grid techniques were continued and brought into a more refined state. Included were the topics of multisurface transformations together with Boolean operations, pointwise distributions on curves, two-dimensional surface grids embedded in three-dimensions, three-dimensional volume grids and the adaptive strategies of mean value relaxation,

alternating direction, and center of mass relaxation for triangular meshes. Of paramount importance in the various adaptive strategies was the utilization of weighting functions which was studied and still required further development.

In addition to the specific developmental tasks, a major review article was prepared for the Annual Review of Fluid Mechanics [13]. This prestigious publication operates on an invited-only basis and produces one book each January in which various topics of importance are surveyed for the typical practitioner in fluid mechanics. More important than the prestige is the rather wide readership, and therefore, the opportunity to solidly establish the role of grid generation in fluid mechanics simulation and to present the fundamental structure and concerns of the topic. The guidelines appropriately given by the publisher were to develop the significant aspects of grid generation rather than to attempt a comprehensive account of everything that was done. It is interesting to note that previous reviews had taken the comprehensive route and had resulted in somewhat lengthy and unwieldly manuscripts. The current review, by contrast, was shorter and I believe is easier for an uninitiated person to follow and to quickly gain a suitable perspective of grid generation.

A further project which was related to the specific developmental tasks was the selection of suitable computer equipment to use for those tasks in the future. The funds were supplied by a DoD equipment funding grant under a program for DoD research at universities. Due to the long lead time between the proposal stage

and the funding stage combined with a rapidly changing technology, an evaluation had to be conducted to obtain the best possible equipment for the alloted funds. For the generation of three-dimensional and adaptive grids, the IRIS by Silicon Graphics was selected over the originally proposed Appolo System.

Under the third grant period from October 1, 1984 to September 30, 1985, the main activity was placed upon the development of weighting functions that produce local controls. These functions were established for arbitrary space curves both in an a priori sense [12] and in an a postiori sense [3]. The results from the curve studies have also provided the foundation for the two and three-dimensional studies [4] and [2] pursued under the final grant period.

In the a priori case [12], the capability to accurately partition the available grid points among various properties was established along with the simultaneous specification of grid spacing from the boundaries. The properties consisted of a prescribed level of curvature clustering together with an arbitrary number of assigned local clusters. While the curvature level is given by a single constant, the local clusters are defined by four constants: one for each endpoint, one for the center, and a final one for the intensity. This permits the use of clusters which can be asymmetric and can have arbitrary intensities. To enable a reasonable interpretation of intensity, the associated constant is simply converted into the number of points assigned to it. While the underlying coordinate transformation is obtained generally by a numerical process, the specific case of vanishing curvature was developed by means of closed

form algebraic expressions. In the theoretical development of [12], the closed form expressions were used to readily identify the key elements in the iterative process by which appropriate constants are determined in order to match a given endpoint spacing. Altogether, this method provided a considerable degree of flexibility.

Once a grid has been generated along a curve, it might not appear the way that we anticipated it to since, for example, our earlier choice of defining constants for a transformation is somewhat limited by our intuitive estimate of what should be reasonable. A case in point would be the desire for a reasonable alignment of points with those of one or more other curves. As a consequence, we need an operation by which the pointwise distribution along a given curve can be modified in a purely local manner. Thus, we generate an initial grid in the best way possible and then modify it with a postiori local manipulations. This leads to the development of weights which can be applied to alter only those points on a chosen segment. On each chosen segment, a single clustering operation was established. Such operations can be applied either in sequence or with some simultaneity. The sequential application is ideally suited to an interactive graphical environment while the simultaneous application is more efficiently done in an automatic manner. The development of the weights and the associated transformations is given in [3].

In addition to the developments in the theory of weighting functions, a number of grid generation techniques have been structured in three-dimensions and programmed on the IRIS 2500 graphical workstation. The techniques include the multisurface transformation,

tensor products of multisurface transformations, various interpolants for such transformations, mean value relaxation, inverse mean value relaxation, and alternating direction strategies.

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